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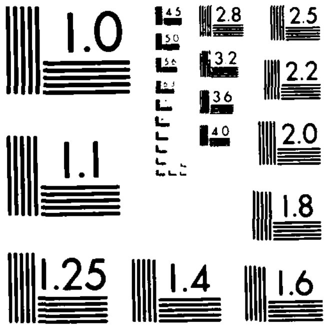

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POSITIVE-PRESSURE VENTILATOR SYSTEMS AT HIGH ALTITUDE: A PRELIMINARY STUDY

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Preliminary studies of a computer model of the cardiorespiratory system and actual measurement of mechanical-ventilator output variables were used to formulate tentative conclusions and recommendations for future studies. In the computer simulation, we derived a series of equations to represent the effect of altitude on predicted arterial oxygen partial pressures (PO_2). For three ventilatory devices (BEAR 1, BIRD MARK 7, MA-1), we measured ventilator output variables at simulated altitudes of 0 to 40,000 ft (12,000 m) in a hypobaric chamber. All three ventilators performed adequately at a simulated altitude of 8,000 ft (2400 m). Iso-shunt curves predict that in a fixed shunt range of 30% to 60%, the transition from ground to 8,000 ft would result in only a moderate effect on PO_2. However, the transition could result in significantly reduced PO_2's at 8,000 ft if the original venous admixture had a large, nonfixed component. Iso-shunt curves predict dangerously low arterial PO_2's at 35,000 to 40,000 ft for all patients, even if ventilatory devices continue to adequately

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19. **ABSTRACT** (continued)
function and fractional inspired oxygen level is 1.0. At high altitude, the volume output of the two volume-cycled ventilators changed significantly. Future evaluations of ventilators and ventilator-patient systems should include attempts to estimate what changes may occur because of decreasing gas density and atmospheric pressures on the patient, the ventilator, and the ventilator-patient system.

POSITIVE-PRESSURE VENTILATOR SYSTEMS AT HIGH ALTITUDE:
A PRELIMINARY STUDY

INTRODUCTION

The USAF Military Airlift Command (MAC) is charged with air evacuation of injured and ill patients in times of war and peace. In recent years the types of patients eligible for transport have expanded to include those with illnesses or injuries that require full-time mechanical support of respiratory functions with closed-system positive-pressure mechanical ventilators. The clinical condition of some patients meets the criteria of the Adult Respiratory Distress Syndrome (ARDS), which is characterized by low pulmonary compliance and poor gas exchange. Respiratory support of such patients in a sea-level environment may require a combination of high-pressure mechanical ventilation and high inspired oxygen tensions. During air evacuation, these patients are routinely exposed to cabin pressures equivalent to 8,000 ft (2400m) standard atmosphere (564 torr); and during rapid cabin decompression, to pressures equivalent to 40,000 ft (12,000m) standard atmosphere (141 torr). Concern that such environmental situations will exhaust already strained machine and physiological reserves, with potential damage to transported patients, has prompted this evaluation of the effects of altitude on the mechanical performance of ventilators and the functioning of already damaged physiological gas-exchange systems.

This report presents an initial evaluation of known and potential problems of using mechanical ventilator systems with ARDA patients in high-altitude environments.

A-1

ADULT RESPIRATORY DISTRESS SYNDROME

ARDS has been a well-recognized clinical entity since the late 1960s. Several recent reviews and textbooks outline current understanding of its etiology, pathophysiology, physiology, clinical course, and treatment (1-4). ARDS may be defined as a diffuse lung injury resulting in noncardiac (normal pulmonary capillary pressure) pulmonary edema and acute respiratory failure. The clinical physiology of severe ARDS is characterized by three phenomena: 1) arterial hypoxemia secondary to ventilation-perfusion mismatch and intrapulmonary shunting, often with a calculated shunt fraction greater than 50%; 2) an increase in physiologic deadspace, with deadspace to tidal volume ratios up to and sometimes exceeding 0.5; and 3) decreased pulmonary compliance, as low as 20 ml/cm H_2O in severe cases (2).

There is no specific treatment for ARDS (2,4). The clinical management is directed towards maintaining adequate tissue oxygenation through respiratory and circulatory support until the primary injury is sufficiently healed. Respiratory support includes providing high inspired oxygen concentrations, positive-pressure mechanical ventilation, and often the use of positive end expiratory pressure (PEEP). The major objective of respiratory support is to obtain optimal distention of the alveoli and thus reverse alveolar collapse. Because of the low pulmonary compliance and high physiologic deadspace, positive-pressure ventilation (PPV) causes relatively high (compared to normal lungs) inspiratory airway pressures, often on the order of 60-70 cm H_2O.

With regard to the transient exposure (at most several hours) of ARDS patients to high altitudes, two atmospheric variables assume importance. The first is barometric pressure, which decreases as altitude increases, as shown in Table 1. The concentration of oxygen remains relatively constant as altitude increases, so the decrease in barometric pressure results in a corresponding and proportional decrease in the partial pressure of oxygen. Second (also seen in Table 1), the environmental temperature decreases with increasing altitude. The low temperatures that would exist in a depressurized aircraft at 40,000 ft might assume significance for patients and ventilators.

TABLE 1. DECREASING ATMOSPHERIC VARIABLES AND TEMPERATURE WITH CORRESPONDING INCREASED ALTITUDE

Altitude (ft [m])	Barometric Pressure (torr)	PO_2(21% O_2) (torr)	Temperature (^oF)
0	760.0	159.2	59.0
8,000 [2,400]	564.6	118.6	30.5
10,000 [3,000]	522.8	109.8	23.3
20,000 [6,100]	349.5	73.4	-12.3
30,000 [9,100]	226.2	47.5	-48.0
40,000 [12,200]	141.2	29.6	-69.7

NOTE: Values taken from ICAN Standard Atmosphere, 1954; PO_2 calculated assuming percentage O_2 is constant at 21%

From the above considerations, we might anticipate two major problems relative to high-altitude exposure of an ARDS patient supported by a mechanical ventilator. First, at any given inspired oxygen concentration, the partial pressure of inspired oxygen would decrease as altitude increased. This should result in worsened oxygen transport because the partial pressure of oxygen in the alveoli is the important factor in oxygen transport across the lung. Second, if the performance of the mechanical ventilator system should suffer a decrement at higher altitudes, the tidal volume delivered to the patient's lung might decrease. This could result in further alveolar collapse and decreased gas exchange.

To explore the effects of decreasing inspired oxygen tension on gas exchange, we generated the graphs in Figures 1-4. These figures present iso-shunt lines relating arterial oxygen tension and saturation of arterial hemoglobin to altitudes up to 40,000 ft. They are intended to demonstrate the consequences of taking a patient-ventilator system to different altitudes

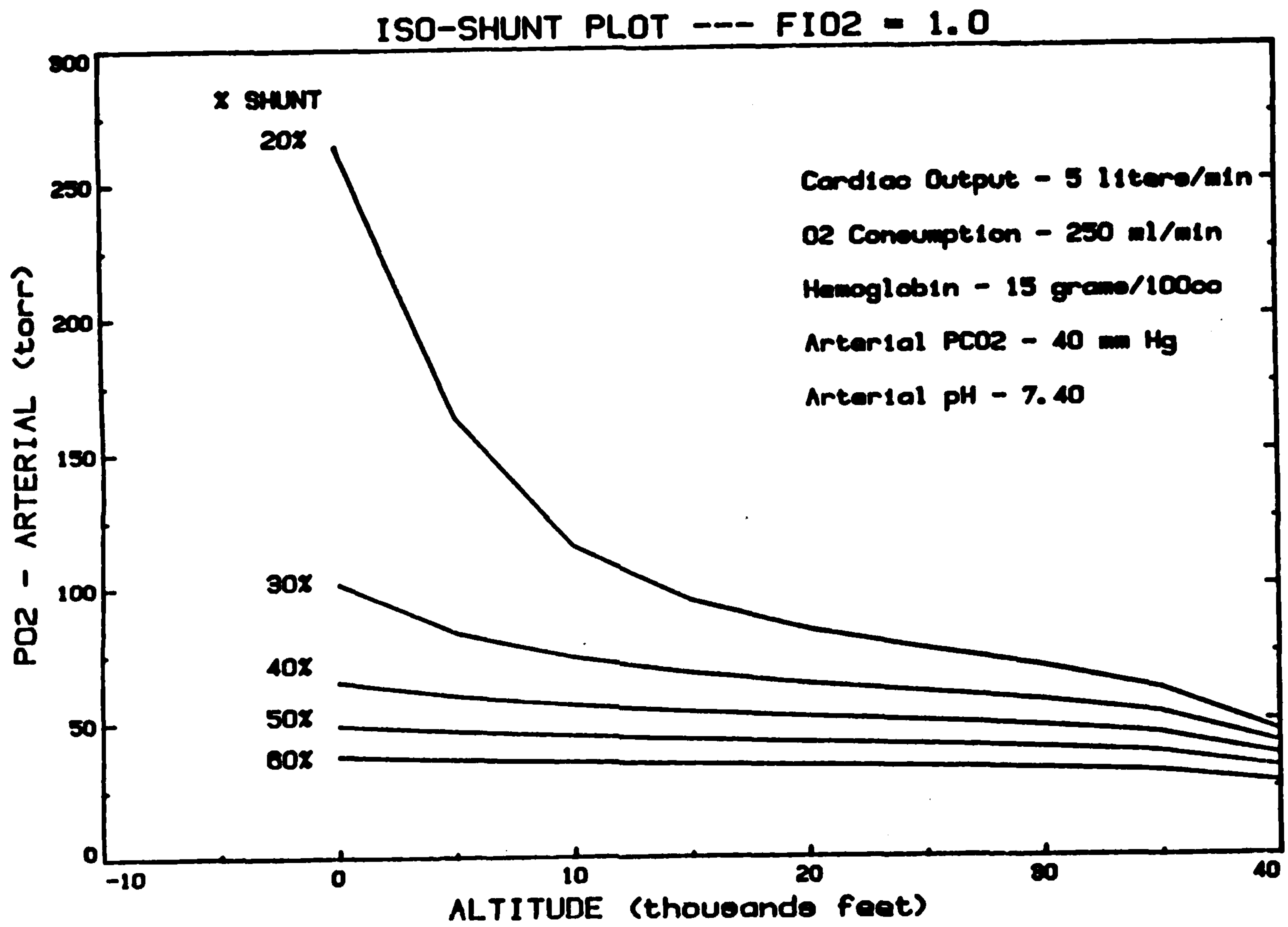

Figure 1. Arterial oxygen tension at 0 to 40,000-ft altitude with FIO_2 = 1.0.

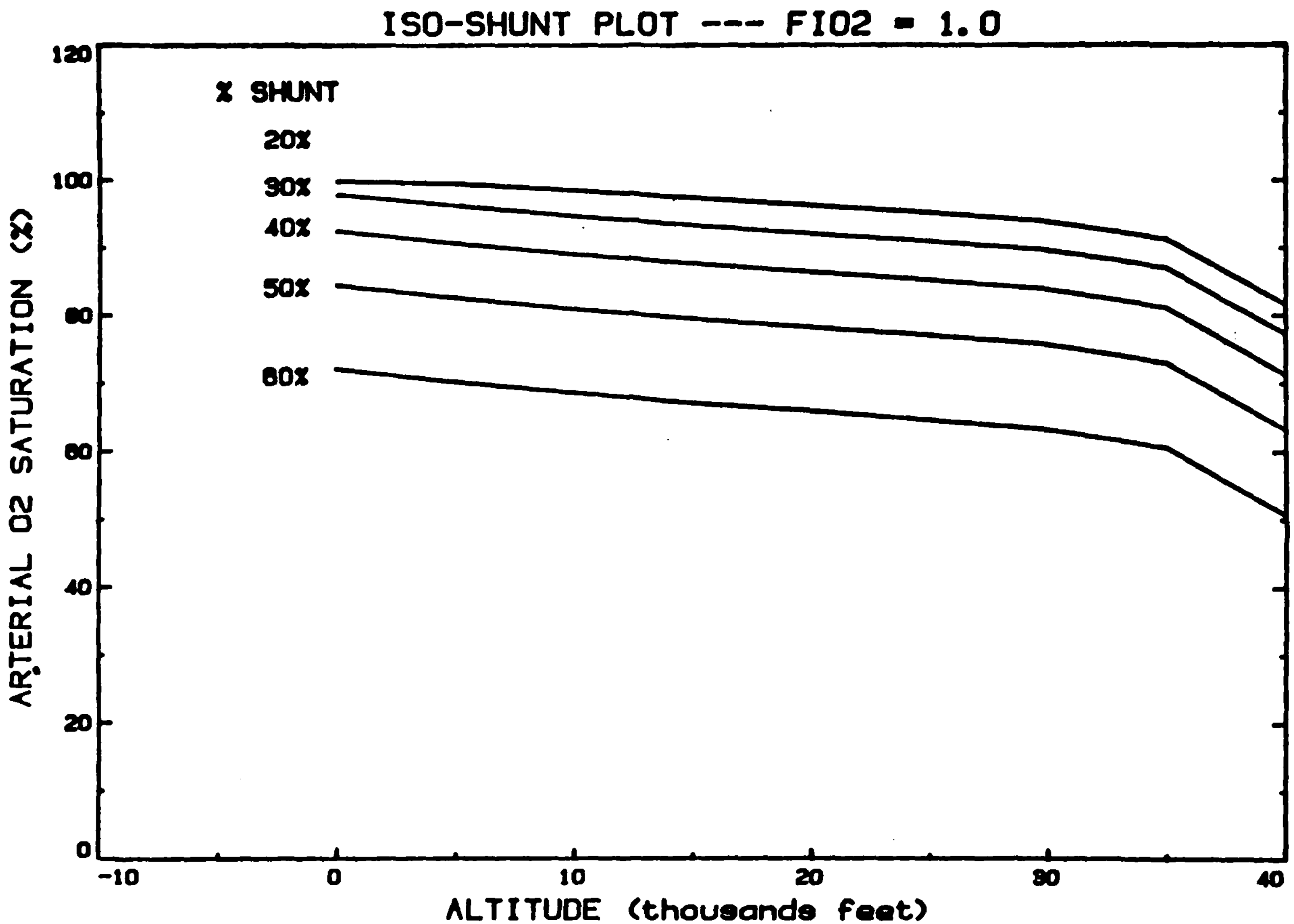

Figure 2. Arterial hemoglobin saturation at 0 to 40,000-ft altitude with FIO_2 = 1.0.

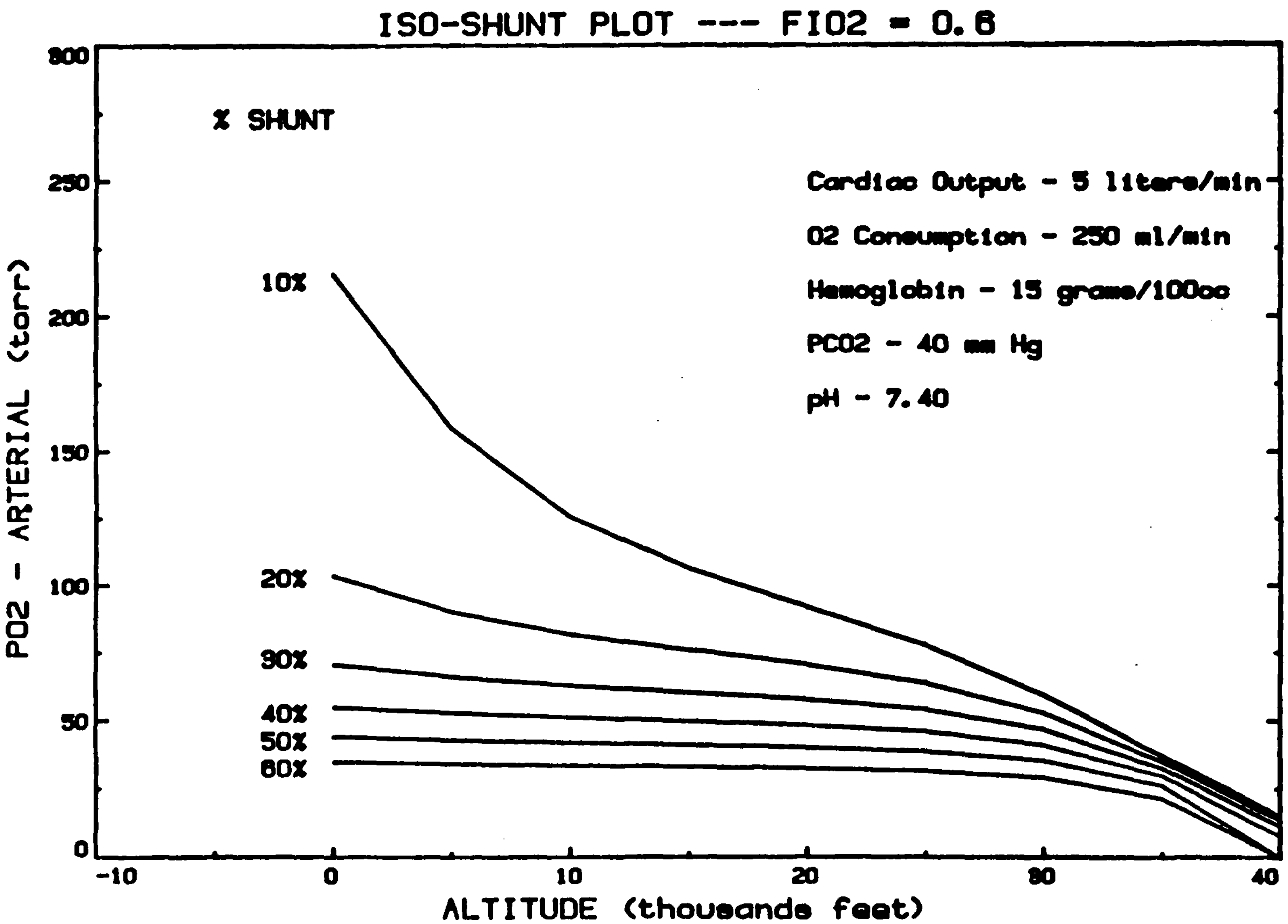

Figure 3. Arterial oxygen tension at 0 to 40,000-ft altitude with $FIO_2 = 0.6$.

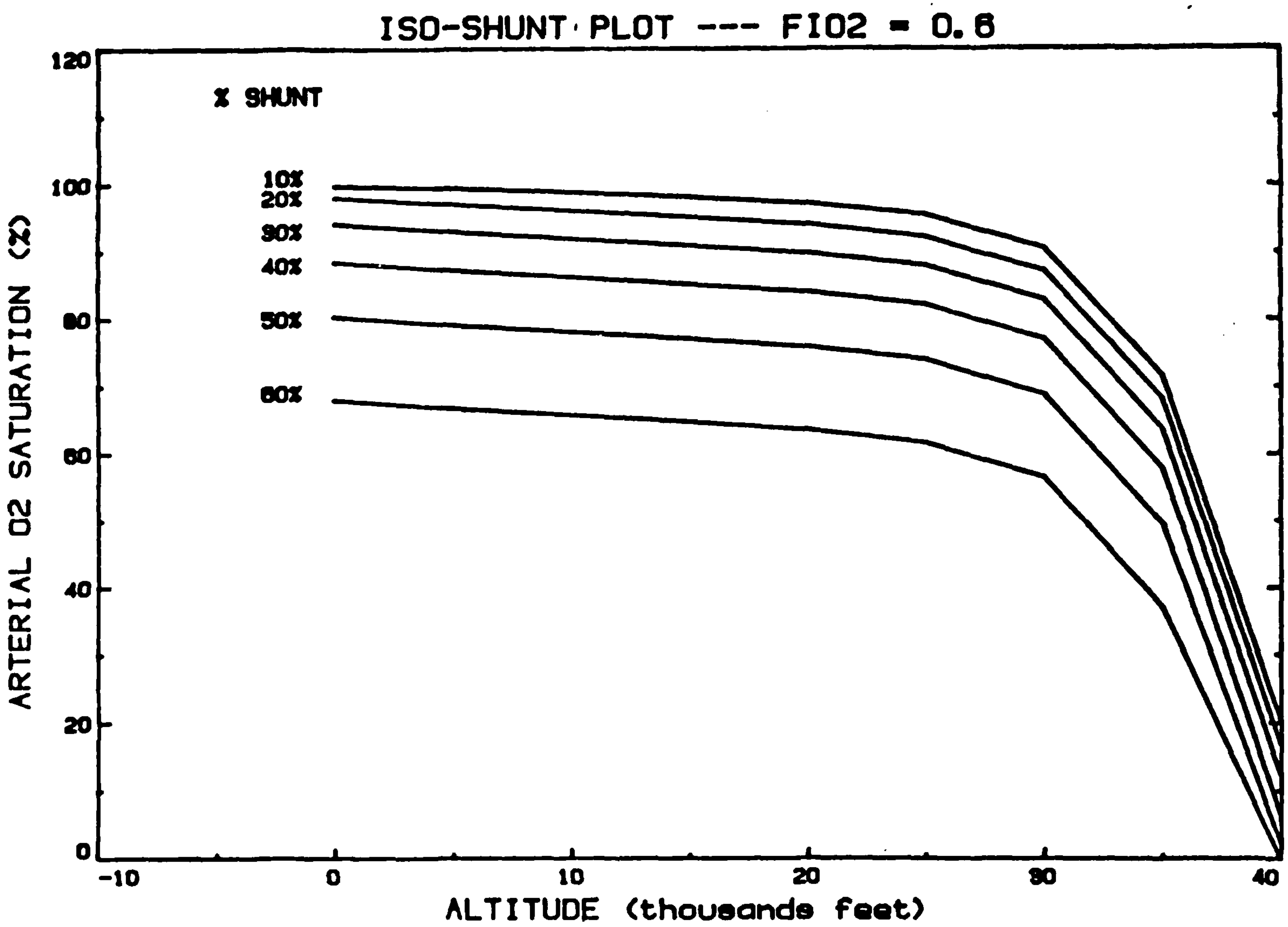

Figure 4. Arterial hemoglobin saturation at 0 to 40,000-ft altitude with FIO_2 = 0.6.

without changing the fraction inspired oxygen supplied. In generating the graphs, we assumed that delivered tidal volume, fraction inspired oxygen (FIO_2), cardiac output, and rate of oxygen consumption remained constant on going to higher altitudes. In addition, the iso-shunt lines assume fixed venous admixture (i.e. anatomic shunt) and steady-state conditions. The FIO_2 values are consistent with values that ARDS patients undergoing transport might receive.

In relating to patients with ARDS, the iso-shunt lines of 30% to 60% are of interest (2). In going from sea level to 8,000 ft, both arterial oxygen tension and saturation decrease but perhaps not in clinically significant amounts. However, as altitudes of 30,000 to 40,000 ft are reached, the decrease in arterial oxygenation assumes significant proportions, even with FIO_2's of 1.0.

In a situation where arterial hypoxemia is secondary to ventilation-perfusion mismatch, the calculated venous admixture generally decreases as the FIO_2 increases (5). Stated another way, the calculated venous admixture increases as FIO_2 decreases. Ascent to higher altitudes has the same effect on inspired oxygen tension as a decrease in FIO_2 at sea level. Therefore for a patient with pure ventilation-perfusion mismatch without a fixed component, ascent to higher altitudes would be expected to result in increasing calculated venous admixture and consequently a greater decrease in arterial oxygen tension and saturation than expected from following a single iso-shunt line. In fact, ARDS patients have been found to have a mixture of fixed shunt and ventilation-perfusion mismatch (5) and to develop a greater percentage venous admixture as the FIO_2 decreases. In Figure 5, equivalent altitudes with 100% O_2 have been substituted for the sea-level FIO_2's for a representative patient reported in reference 5, and the resulting curve is superimposed on iso-shunt lines. This may be considered a prediction of the change in venous admixture that this patient would develop at higher altitudes, and demonstrates that predictions from iso-shunt lines might be conservative in these patients.

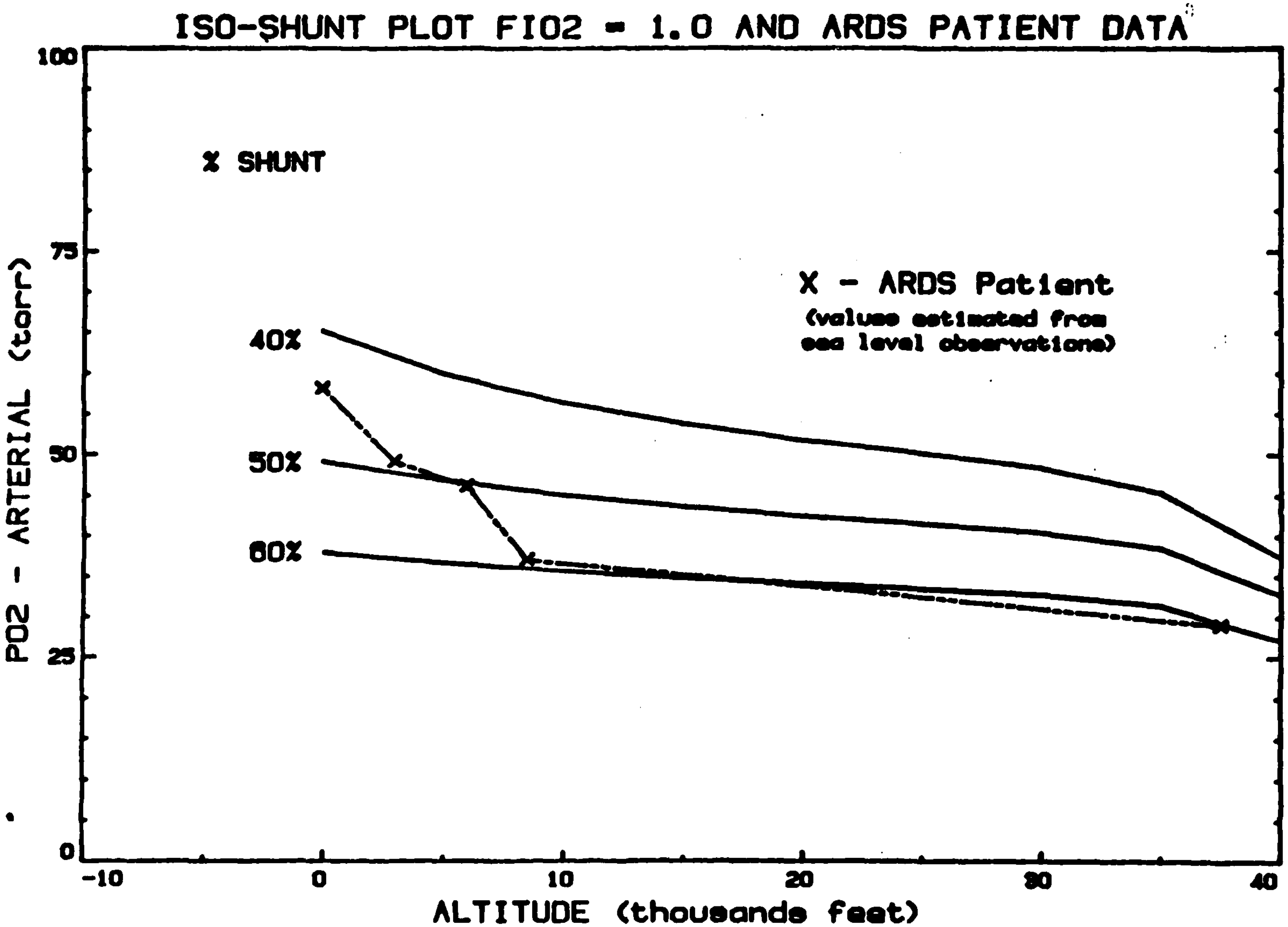

Figure 5. Prediction of venous admixture changes in ARDS patient at different altitudes.

MECHANICAL VENTILATORS AND ALTITUDE

Although the effects of acute exposure to high altitudes on the normal respiratory system have been studied (6,7), the literature contains little concerning lung-injured, ventilator-dependent patients and high altitudes (8). We found only one study (9) that systematically evaluated a ventilator system on a test lung and on animals at high altitudes. In that study a Bird Mark VIII was used to ventilate normal dogs at altitudes up to 34,000 ft. Despite a significant decrease in the ventilation rate as altitude increased, adequate gas exchange was achieved in the animals. In lung-injured patients, however, such results with regard to oxygen exchange might not be achieved (as previously noted from reference to the iso-shunt diagrams).

Of the various methods used to effect ventilation in ARDS patients, the most used today is that of creating a positive intrapulmonary pressure in the presence of atmospheric extrathoracic pressures (2,4,11). Many commercial ventilators that use this principle are available (11,12), also standards and methods for evaluating their mechanical functioning in a sea-level environment (10,13). Positive-pressure ventilators can be classified by what cycles the ventilator into the inspiratory phase (patient, manual, or time), what limits the inhalation phase and switches to exhalation (volume, pressure, time, manual), and what type of drive mechanism is used to effect inhalation. This last characteristic includes the ultimate force producer (electric motor or pneumatic) as well as whether the gas is delivered as a result of a decrease in volume of some device in the ventilator (bag, piston, bellows) or as a result of flow from a compressed-gas source and/or venturi effect.

In a preliminary study at the USAFSAM hypobaric chambers, we evaluated three positive-pressure ventilators in an initial effort to devise a system for testing ventilator mechanical performance at high altitudes (up to 40,000 ft). A Vent-Aid test lung was used as the mechanical load. This device has linear compliance characteristics that can be varied from 20 to more than 1000 cc/cm H_2O, parabolic resistance characteristics, and a functional residual capacity (FRC) of 1800 cc. To measure intrapulmonary and airway pressures, we used Hewlett Packard 270 pressure transducers and a Hewlett Packard 7658

respiratory system with chart recorder output. We measured inspiratory flows with a Fleisch #3 pneumotach, Validyne DP 45-10 differential pressure transducer, and CD12-871 demodulator, and displayed the flows on the Hewlett Packard 7658 respiratory system chart recorder. We measured inspired volumes in three ways: First, integrated the pneumotach flow signal with a Hewlett Packard 8815A respiratory integrator; second, noted the maximum inspiratory volume on the Vent-Aid volume indicator; and third, generated a pressure-volume curve for the Vent-Aid for each compliance setting used and calculated the volume from the observed peak inspiratory intrapulmonary pressure. We considered the values obtained from the second and third methods as representing the tidal volume delivered to the lung.

The pneumotach was calibrated with a Rotometer calibrating flowmeter, and the flow integral, by integrating the flow for measured periods of time. We checked the volume calibration routine for accuracy by comparing it with results obtained from using a volumetric piston. Pressures were calibrated with water columns. Testing with an electrically driven sinusoidal flow generator showed the flow and volume measurements to be valid up to 40,000 ft in the hypobaric chamber.

For these tests, the ventilators were set up at sea level, to deliver a tidal volume of approximately 1 L. With ventilator settings unchanged, the chamber was taken to successively higher altitudes, pausing at 8, 20, 30, and 40 thousand ft for measurements. This was intended to mimic a ventilator-patient system which is set up at one altitude and transits unattended to another. We chose a compliance of 20 cc/cm H_2O and normal resistance to represent ARDS patients.

The results of four representative studies are presented in Tables 2-4. Table 2 presents results for the MA-1. This ventilator delivers gas from an internal bellows that fills to a volume of 2 L prior to beginning inspiration and empties to a preset volume to terminate inspiration. An electric compressor pump provides a source of compressed air used to empty the bellows. As seen in Table 2, tidal volumes, peak lung pressures, and peak flows decreased with increasing altitude. The tidal volumes from the pneumotach

with flows recorded with the gas at pressures from ambient to ambient-plus-peak-pulmonary, are higher than those from the pressure-compliance calculations where the tidal volumes are obtained at ambient-plus-peak-pulmonary pressure and thus with the gas in a more compressed state. Tidal volume delivered between 35,000 and 40,000 ft declines abruptly, probably due to an inability of the gas compressor system to generate the required pressures above 35,000 ft.

TABLE 2. MA-1 VENTILATOR TEST RESULTS

Altitude (ft)	Cycle Rate (/min)	I/E Ratio	Tidal Vol. Delivered (cc)	Tidal Vol. Pneumotach (cc)	Peak Flow (L/min)	Peak Lung Pressure (cm H_2O)
0	7.9	0.49	1000	980	40	50.0
8,000	8.0	0.49	910	933	36	45.5
20,000	8.0	0.53	740	817	32	37.0
30,000	7.9	0.51	580	700	28	29.0
35,000	7.9	0.96	480	617	24	24.0
40,000	8.0	-	10	10	-	0.5

NOTE: Compliance = 20 cc/cm H_2O, FRC = 1800 cc, tubing vol. = 300 cc
I/E ratio = inspiratory time/expiratory time
Tidal vol. delivered: Derived from peak lung pressure and compliance; represents volume at ambient pressure + peak pressure
Tidal vol. pneumotach: Integral of pneumotach flow signal; represents volume at pressures between ambient and ambient peak pressures

In a bellows-lung system with the bellows loaded with gas at ambient pressure, the extent to which the gas is compressed after the bellows empties to the lung increases as the ambient gas pressure decreases. Because of this, it is difficult to judge whether the decrement in tidal volume observed with the MA-1 up to 35,000 ft is the result of compression (and therefore to be expected on physical grounds) or of poor compressor performance or other mechanical failure. In an attempt to evaluate this, we developed an abstract piston ventilator model (Appendix) that allowed calculation of delivered tidal volumes in an unattended ventilator going to altitude. Figure 6 presents results with the variables set to mimic the MA-1--Vent-Aid system, and Figure 7 compares observed results with those predicted. The disparity of results indicates that altitude-dependent effects other than compression might be present with this ventilator.

Table 3 presents the results of a trial with the Bear 1. This is a volume-cycled ventilator that delivers gas from a compressed source, supplied either from external sources or from an integral electric compressor. In this trial the compressed gas was from an external source. A vortex shedding flowmeter measures and integrates the volume and cuts off the gas flow when the preset volume is reached. As with the MA-1, although not as much, delivered tidal volumes decrease with increasing altitude. The Bear 1 is not a bellows ventilator, so the piston model is not an appropriate tool here, although it is interesting that a comparison with the results of this model (Figure 8) shows close agreement.

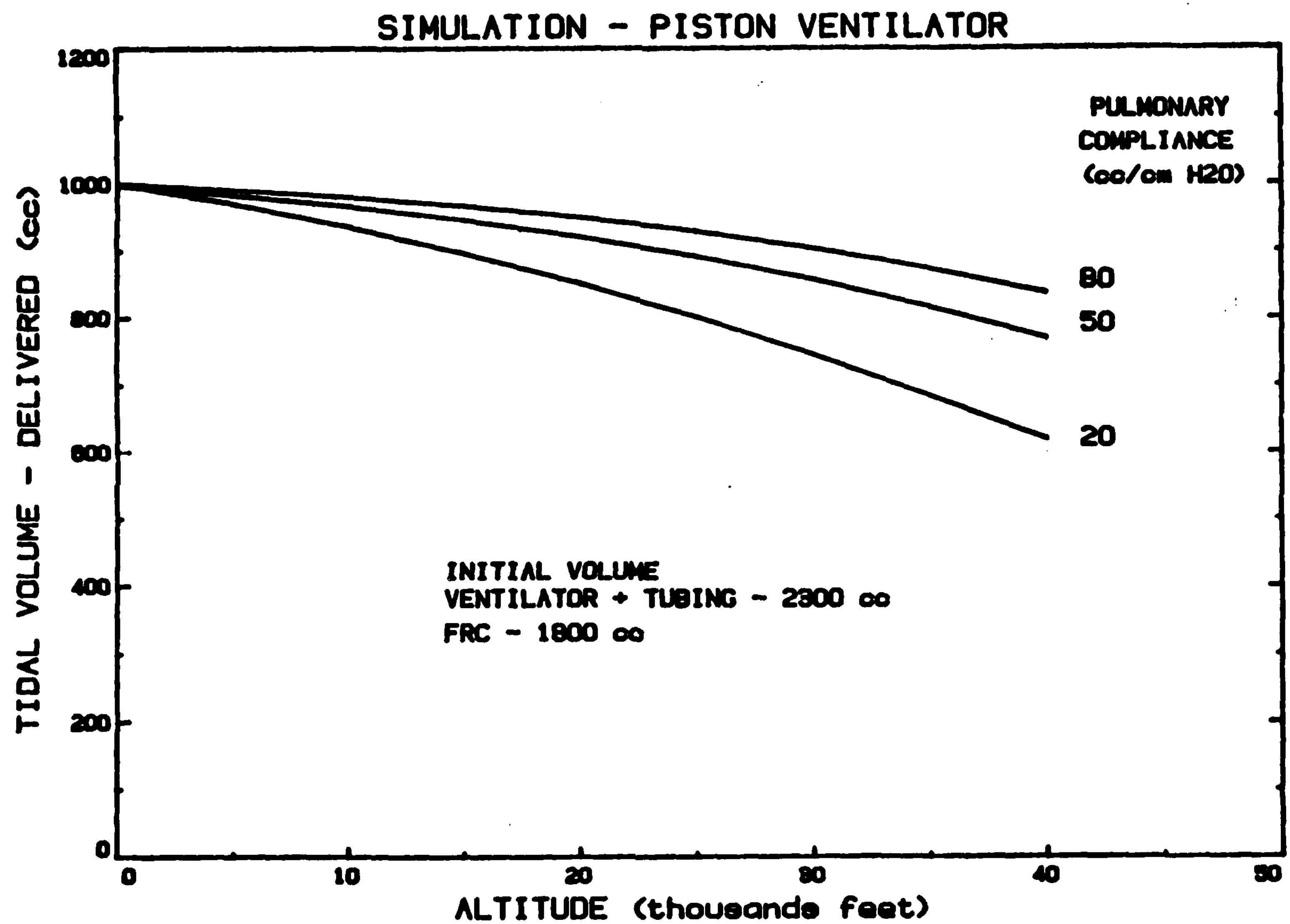

Figure 6. Predicted (calculated) tidal volumes delivered in ventilator at altitudes 0 to 40,000 ft.

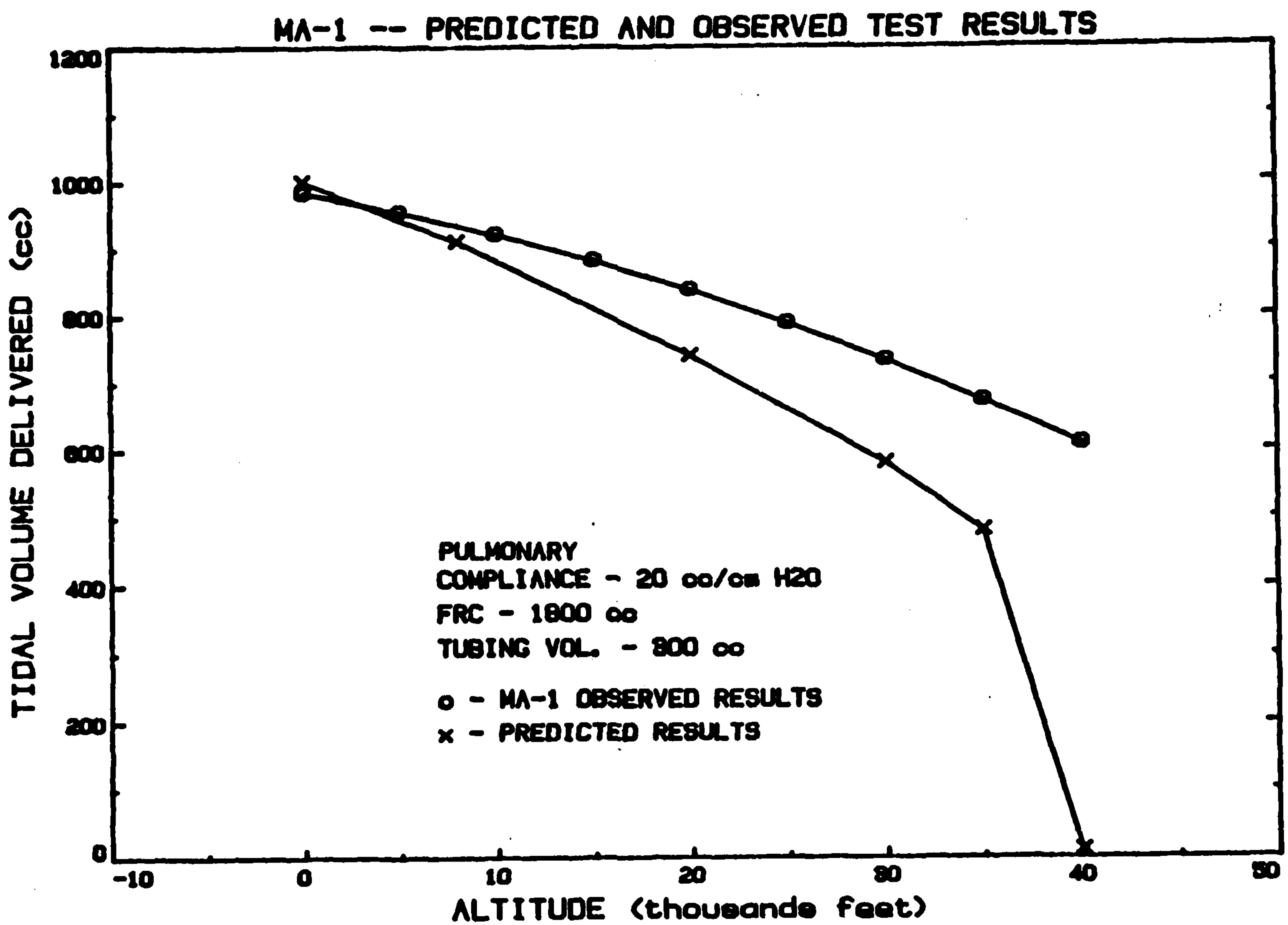

Figure 7. Comparison of predicted and observed tidal volumes (MA-1--Vent-Aid system).

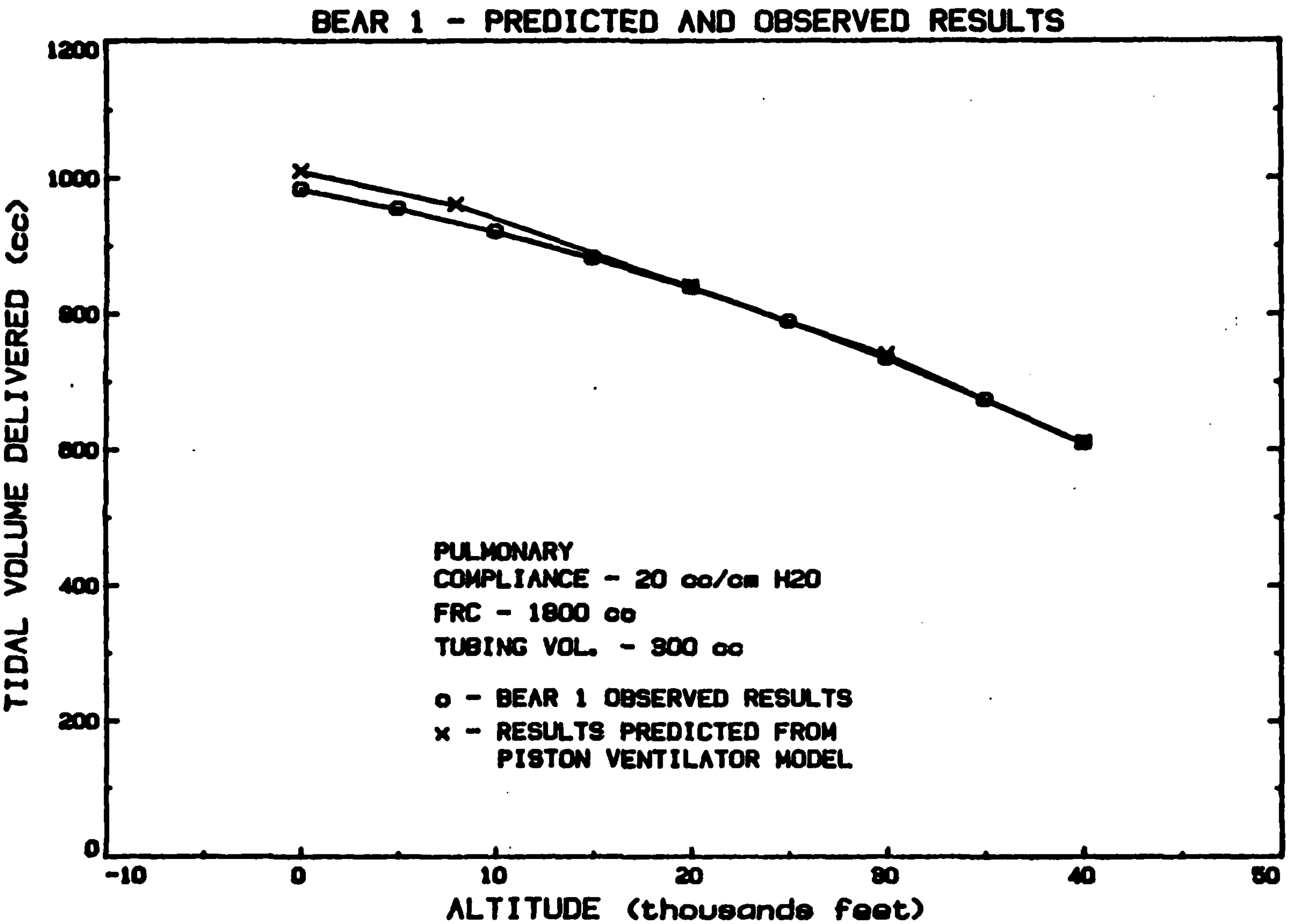

Figure 8. Comparison of predicted (piston ventilator model) and observed (Bear 1, compressed-source volume-cycled ventilator) tidal volumes.

TABLE 3. BEAR I VENTILATOR TEST RESULTS

Altitude (ft)	Cycle Rate (/min)	I/E Ratio	Tidal Vol. Delivered (cc)	Tidal Vol. Pneumotach (cc)	Peak Flow (L/min)	Peak Lung Pressure (cm H_2O)
0	8.1	0.47	1010	1000	36	50.5
8,000	8.0	0.38	960	973	36	48.0
20,000	8.0	0.30	840	933	40	42.0
30,000	8.0	0.23	740	900	48	37.0
40,000	8.1	0.18	610	873	54	30.5

NOTE: Compliance = 20 cc/cm H_2O, FRC = 1800 cc, tubing vol. = 300 cc
I/E ratio = inspiratory time/expiratory time
Tidal vol. delivered: Derived from peak lung pressure and compliance; represents volume at ambient pressure + peak pressure
Tidal vol. pneumotach: Integral of pneumotach flow signal; represents volume at pressures between ambient and ambient peak pressures

Tables 4 and 5 present the results of a trial with a Bird 7 pressure-cycled pneumatic ventilator at two pulmonary compliance settings. If the pulmonary compliance characteristics do not change with altitude, the tidal volumes delivered from a pressure-cycled ventilator should remain constant because the transthoracic pressure difference is what cycles the ventilator. This appears to be the case with the Bird 7. However, on both trials the cycle rate decreased. Our finding is similar to that of Kirby et al. (9) with the Bird Mark 8. As described in that paper, the rate decrease is likely secondary to the effects of decreased gas density on the rate-setting mechanism.

TABLE 4. BIRD 7A VENTILATOR TEST RESULTS -- LOW LUNG COMPLIANCE

Altitude (ft)	Cycle Rate (/min)	I/E Ratio	Tidal Vol. Delivered (cc)	Tidal Vol. Pneumotach (cc)	Peak Flow (L/min)	Peak Lung Pressure (cm H_2O)
0	8.2	0.46	1000	967	60	50.0
8,000	7.7	0.37	1000	1000	64	50.0
20,000	7.0	0.24	1000	1083	76	50.0
30,000	6.4	0.19	1020	1217	88	51.0
40,000	5.9	0.15	1020	1417	104	51.0

NOTE: Compliance = 20 cc/cm H_2O, FRC = 1800 cc, tubing vol. = 300 cc
I/E ratio = inspiratory time/expiratory time
Tidal vol. delivered: Derived from peak lung pressure and compliance; represents volume at ambient pressure + peak pressure
Tidal vol. pneumotach: Integral of pneumotach flow signal; represents volume at pressures between ambient and ambient peak pressures

TABLE 5. BIRD 7A VENTILATOR TEST RESULTS--HIGH LUNG COMPLIANCE

Altitude (ft)	Cycle Rate (/min)	I/E Ratio	Tidal Vol. Delivered (cc)	Tidal Vol. Pneumotach (cc)	Peak Flow (L/min)	Peak Lung Pressure (cm H_2O)
0	9.2	0.27	1050	967	60	21.0
8,000	8.3	0.22	1050	1017	66	21.0
20,000	7.3	0.14	1050	1017	80	21.0
30,000	6.5	0.10	1000	1000	96	20.0
40,000	5.9	0.08	1017	975	112	19.5

NOTE: Compliance = 20 cc/cm H_2O, FRC = 1800 cc, tubing vol. = 300 cc
I/E ratio = inspiratory time/expiratory time
Tidal vol. delivered: Derived from peak lung pressure and compliance; represents volume at ambient pressure + peak pressure
Tidal vol. pneumotach: Integral of pneumotach flow signal; represents volume at pressures between ambient and ambient peak pressures

CONCLUSIONS

This was a preliminary study of the performance of ventilator-lung systems at altitudes, so only tentative conclusions will be drawn and will be such as to point to further research.

First, all three ventilators tested performed adequately at 8,000 ft. In addition, the iso-shunt curves indicate that with shunts in the range of 30% to 60%, transition to 8,000 ft would have a slight effect on arterial PO_2's. However, if the original venous admixture had a large non-fixed component and if the prediction in Figure 5 is valid, this transition might result in significantly reduced arterial PO_2's.

Second, as predicted from the iso-shunt curves, patients with large shunts might be expected to have dangerously low arterial PO_2's at 35,000 to 40,000 ft even if the supporting ventilators adequately maintain delivered tidal volume and the FIO_2 is 1.0. The two volume-cycled ventilators had significant decreases in tidal volumes at these altitudes. In ARDS patients, this could result in alveolar collapse and further decreased arterial PO_2's which might persist for a period after lower altitudes are attained.

Third, in evaluating the performance of individual ventilators at altitude, some attempt should be made to estimate what effects decreasing gas density and pressure should have. These would set the limit for the minimal changes to be expected. Such an estimate will require a model of how the particular ventilator functions in a complete system so that the predicted changes can be calculated.

Finally, some consideration should be given to the ability of ventilators to function at the low temperatures expected at altitudes of 35,000 to 40,000 ft.

REFERENCES

1. Bone, R.C., ed. Adult respiratory distress syndrome. Clin Chest Med, vol. 3, 1982.

2. Balk, R., and Bone, R.C. The adult respiratory distress syndrome. Med Clin North Amer 67:685-700, 1983.

3. Hurewitz, A., and Bergofsky, E.H. Adult respiratory distress syndrome physiologic basis of treatment. Med Clin North Amer 65:33-51, 1981.

4. Guenter, C.L., and Welch, M.H. Pulmonary Medicine. Philadelphia: Lippincott, 2d ed., 1982.

5. Briscoe, W., Smith, J., and Bergofsky, E.H. Catastrophic pulmonary failure. Amer J Med 60:248, 1976.

6. Del Vecchio, R. Physiological Aspects of Flight. New York: Dowling College Press, 1977.

7. Randel, H. Aerospace Medicine. Baltimore: Williams and Wilkins Co., 1971.

8. Byrd, R., Burns, J., and McElvain, W. Air transport of patients in respiratory failure. Aerospace Med 41:934-937, 1970.

9. Kirby, R.R., DiGiovanni, A., and Bancroft, R.W. Function of the bird respirator at high altitude. Aerospace Med 40:463-469, 1969.

10. American National Standards Institute. ANSI 279.7-1976, Breathing Machines for Medical Use. New York: ANSI, 1976.

11. Mushin, W.W., Rendell-Baker, L., Thompson, P.W., and Malpleson, W.W. Automatic Ventilation of the Lungs. Oxford: Blackwell, 1980.

APPENDIX

EFFECTS OF ALTITUDE ON PERFORMANCE OF PISTON VENTILATOR

Vlung - Lung volume
Vlung1 - Volume in lung at beginning of inspiration (FRC)
Vlung2 - Volume in lung at end of inspiration
Vv - Ventilator volume
Vv1 - Volume in ventilator at beginning of inspiration (Vvmax)
Vv2 - Volume in ventilator at end of inspiration
Pv - Pressure in ventilator
Pv1 - Pressure in ventilator at beginning of inspiration
Pv2 - Pressure in ventilator at end of inspiration
Plung - Pressure in lung
Plung1 - Pressure in lung at beginning of inspiration
Plung2 - Pressure in lung at end of inspiration
Pamb - Ambient pressure at current altitude
Clung - Total pulmonary compliance (ml/cm H_2O)
M - Mass of gas
Mv - Mass of gas in ventilator (piston + tubing)
Mlung - Mass of gas in lung
Ms - Mass of gas in the system (Mv + Mlung)
PV=nRT - Ideal Gas Law

We want a model to demonstrate the relationship of ambient gas pressure to the volume delivered from a piston ventilator to a lung in a closed ventilator-tubing-lung system.

For the purpose of this model, assume a system composed of a piston-type, volume-cycled, positive-pressure ventilator connected in series through noncompliant tubing to a pulmonary system with linear compliance characteristics and a constant residual volume. The tubing is assumed to have

constant volume, so the ventilator will be defined to consist of the ventilator piston and the conducting tubing. Functionally, the ventilatory cycle has two states and two transitions. In state #1, the ventilator has filled to maximum (Vv1) at a pressure equal to Pamb and the lung has emptied to its functional residual capacity (Vlung1) at a pressure also equal to Pamb. In state #2, the ventilator has emptied to Vv2 and the lung has filled to Vlung2. In state #2, pressures in the lung, tubing, and ventilator piston are equal. The transition from state #1 to state #2 is inspiration, and from #2 to #1 is expiration. Vv2 may be greater than the volume of the tubing, so the ventilator piston may contain residual gas at end of inspiration.

Since this model is being used to predict values for an artificial lung, no water vapor will be assumed to be added by the lung; and the lung, ventilator, and ambient temperatures will be the same.

DERIVATION

First, assume the Ideal Gas Law is valid:

$$PV = nRT \qquad \text{A-1}$$

$$PV = KM \qquad \text{(T constant, n proportional to M)} \qquad \text{A-1a}$$

The lung and ventilator are connected in series and under conditions of no flow in the system

$$Plung = Pv \qquad \text{A-2}$$

Prior to beginning inspiration, the ventilator fills to maximum (Vv1) at the ambient gas pressure. Therefore,

$$Pv1 = Plung\ 1 = Pamb \qquad \text{A-3}$$

Next, define the compliance characteristics of the lung by

$$Vlung = Vfrc + Clung\ (Plung - Pamb) \qquad \text{A-4}$$

$$Vlung2 + Vlung1 = Clung\ (Plung2 - Plung\ 1) \qquad \text{A-4a}$$

By rearranging 4a,

$$Plung2 = Plung1 + (Vlung2 - Vlung1)/Clung \qquad \text{A-5}$$

Assuming the system is gas tight during transition from state #1 to state #2, conservation of mass holds:

$$Ms1 = Ms2 \qquad \text{A-6}$$

$$Mv1 + Mlung1 = Mv2 + Mlung2 \qquad \text{A-6a}$$

By substituting eq. A-1a in A-6 and multiplying by K,

$$Pv1(Vv1) + Plung1(Vlung1) = Pv2(Vv2) + Plung2(Vlung2) \qquad \text{A-7}$$

To simplify, use eqs. A-2 and A-3:

$$Pamb(Vv1 + Vlung1) = Plung2(Vv2 + Vlung2) \qquad \text{A-8}$$

Use eq. A-5 to substitute for Plung2 in eq. A-8, then eq. A-3 to substitute for Plung 1:

$$Pamb(Vv1 + Vlung1)$$

$$= (Pam + (Vlung2 - Vlung1)/Clung)\ (Vv2 + Vlung2) \qquad \text{A-9}$$

Solve eq. A-9 for Vlung2:

$$Vlung2 = (-b + \sqrt{(b^2 - 4ac)})/2a \qquad \text{A-10}$$

where

$a = 1$

$b = Pamb(Clung) + Vv2 + Vv1$

$c = -Vlung1(Vv2) - Pamb(Clung)\ (Vv1 + Vlung1 - Vv2)$

Now calculate delivered tidal volume as

$$Vt = Vlung2 - Vlung1 \qquad \text{A-11}$$

Equations A-10 and A-11 allow calculation of delivered tidal volume if ambient pressure, beginning and final ventilator volumes, beginning lung volume, and pulmonary compliance are known.

END
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